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Fisheries harvest and standing stock in a Hawaiian Bay

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Abstract

An 18-month study at Hanalei Bay, Kauai provided unusually valuable quantitative fishery data and concurrent estimates of natural density of reef fish for a complete, small, subsistence/recreational/artisanal fishery on a small, remote island in the tropical mid-Pacific. Catch and effort data were collected using a stratified random sampling design. The commercial surround net fishery targeted mainly coastal pelagic species and accounted for over 70% of the catch. Most other fishing was for recreation or subsistence. Line fishing from shore and boats accounted for much of the effort but produced some of the lowest catches per unit effort (CPUE). The cast net and spear fisheries had CPUE values of more than 1 kg per gear-hour and caught a wide diversity of reef-associated species. Standing stock of reef-associated fishes was estimated from 516 underwater visual censuses. Mean biomass ranged from over 16 kg/100 m^2 in shallow complex habitats to less than 1 kg/100 m^2 in monotypic reef flat habitats. These densities, which are higher than those reported from some more populated, similar areas in Hawaii, may reflect lower fishing pressure in Hanalei. Yield estimates from Hanalei Bay are very low compared to those from many other locations in the Pacific. The small fraction of the overall standing stock that is harvested annually ($\sim$ 1.3%) suggests that most of the fish community is not being severely overfished. Parrotfishes, goatfishes, and surgeonfishes were important components of the fisheries and of the censused communities, suggesting that these target species have not been seriously depleted. The small sizes at which some valued species are caught is a matter of concern for management of these stocks. © 1997 Elsevier Science B.V.

Keywords: Reef fisheries; Coral reef fishes; Hawaii; Fisheries yield

1. Introduction

Interest has grown over recent years in assessing the available stocks of fishes, the actual catches, and the potential sustainable yields from shallow tropical waters that contain coral reefs (Marten and Polovina, 1982; Munro and Williams, 1985; Russ, 1991; Wright, 1993; Dalzell, 1996). These habitats typically support many diverse species, each in relatively low numbers compared to most temperate neritic and open ocean habitats (Munro, 1980; Munro and Williams, 1985). Because of this community structure, and often because of the socioeconomic and cultural characteristics of the nearby human populations, fisheries on these shallow-water communities commonly include many individual fishers. Each fisher typically employs a limited amount of gear and fishing power, but a wide variety of gear is used

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in the fishery to exploit a broad spectrum of species (Munro, 1980; Munro and Williams, 1985; Russ, 1991; Medley et al., 1993). Thus, the character of the fishery is commonly somewhere between subsistence, recreational, and artisanal, rather than conventionally commercial on a large scale.

These characteristics usually cause difficulty in assessing such fisheries, particularly because effort is diffused over such a large base of small producers, and reporting mechanisms are usually crude or nonexistent (Munro, 1980; Acosta and Recksiek, 1989; Russ, 1991; Medley et al., 1993). For these reasons, it is unusual to find useful estimates of catch, fishing effort, and standing stocks (or densities) for a significant portion of any total fishery. Such concurrent estimates are clearly useful for managing particular fisheries. They also contribute to the growth of a small collection of estimates for tropical, neritic, reef-associated fisheries that is beginning to produce some understanding of the nature and potential of such fisheries to contribute to meeting human demands (Marten and Polovina, 1982; Munro and Williams, 1985; Medley et al., 1993). For the latter purposes, data from a variety of locations and situations are desirable. The only consistent long-term source of data of Hawaii's fisheries is the commercial landings database maintained by the State Division of Aquatic Resources (DAR) (Smith, 1993). Hawaii has no recreational saltwater fishing license or reporting requirements, making it difficult to estimate the recreational effort or catch. In an island state such as Hawaii, where as much as 35% of the resident population fishes (Hoffman and Yamauchi, 1972; U.S. Fish and Wildlife Service, 1988), the recreational/subsistence catch may have a large impact on the nearshore marine resources.

The present study, performed at Hanalei Bay on the north coast of Kauai in the Hawaiian Archipelago, provided the unusual opportunity to obtain high quality data over a period of 18 months concurrently on the fishing effort and catch of the complete fishery and the density of the reef fish community. From a management perspective, results are important because no records existed that provided reasonable estimates of the neritic catch. Similarly, no baseline study of fish abundance had been done with sufficient thoroughness and spatial and temporal coverage to estimate densities of the many species on the reefs in the bay. Of broader interest, these results add to the meager store of records of reef fisheries information on stocks and yields from a small, subsistence/recreational/artisanal island fishery on a remote archipelago in the tropical mid-Pacific. Human population and activity were sufficiently low to suggest that the fishery was still operating on a fish community whose structure was not grossly modified by humans as are other more populated areas of Hawaii. Extensive, concurrent field study (much of it with SCUBA) over more than two years provided an unusually comprehensive base of ecological information on the fish populations and habitat (Friedlander et al., 1995; Friedlander, 1996).

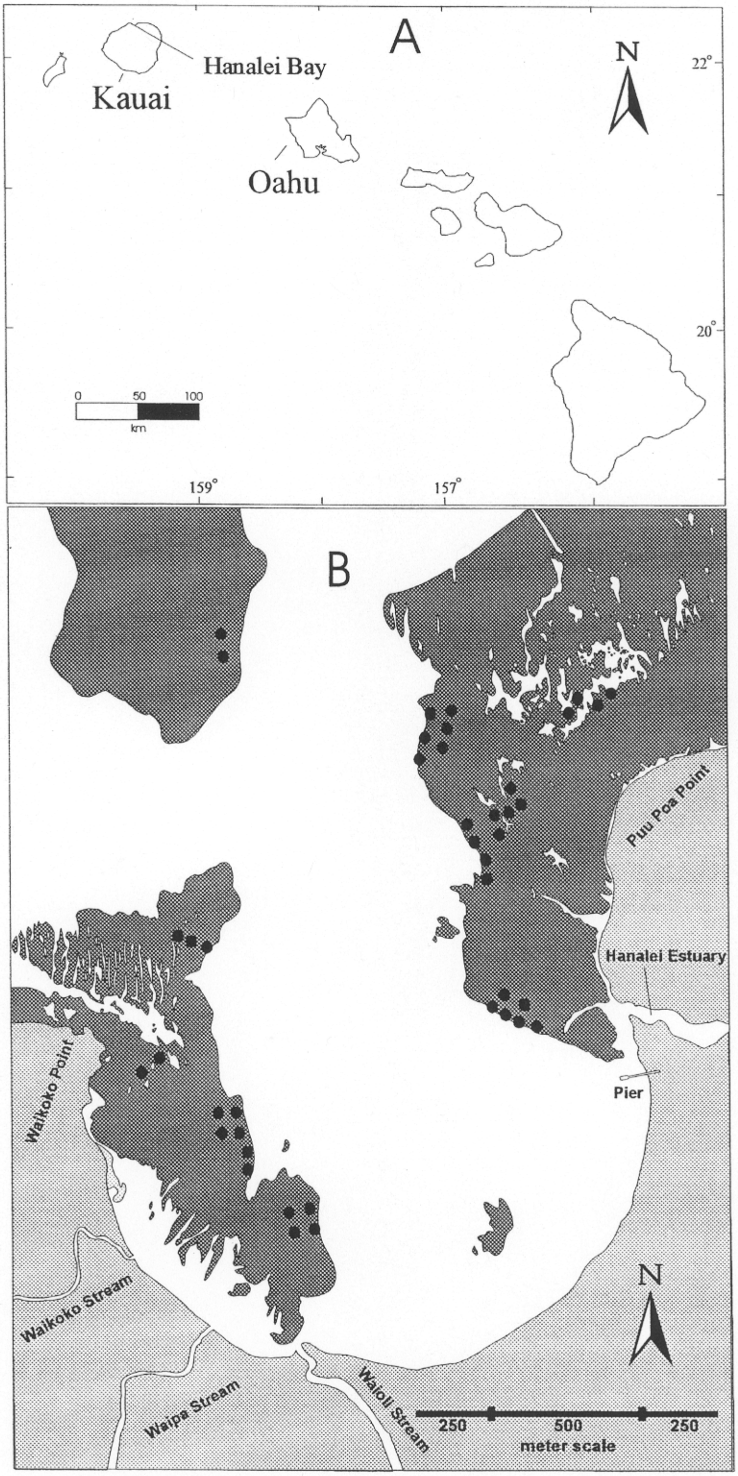
2. Methods

Hanalei Bay is a crescent shaped bay, framed by two rocky points ~ 2 km apart, on the north shore of the island of Kauai (Fig. 1). The bay is characterized by well-developed fringing reefs bordering an extensive area of unvegetated carbonate sediments in the center that stretches from beyond the mouth of the bay to the shoreline in the southeast quadrant. The areas of mostly hard substrate cover approximately 0.75 km^2 of the west side of the bay and 2.89 km^2 of the northeast side.

2.1. Fishery survey methodology

Fishing activities in Hanalei Bay were monitored by remote visual surveillance and creel census of fishers intercepted at shore. From a single vantage point, an observer scanned the bay waters and shoreline frequently on a systematic schedule using binoculars and/or a high-power spotting telescope. The configuration and dimensions of the bay are such

Fig. 1. (A) Location of Hanalei Bay in the main Hawaiian Islands; (B) Map of Hanalei Bay, showing inshore area of the fishery study. Portions of the bay shown in dark stipple are hard-bottom reef tracts. Dark circles indicate locations of benthic transects used for making visual estimates of standing stock.


A
Hanalei Bay
Kauai
Oahu
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22°
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km
159°
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B
Puu Poa Point
Hanalei Estuary
Pier
Waikoko Point
Waikoko Stream
Waipa Stream
Waioli Stream
N
250
500
250
meter scale

that this approach permitted detection of fishing vessels and individual fishers almost anywhere in the bay. Data included a record of each boat and fisher (including people fishing from shore or entering the water on foot), locations and corresponding times of day, type and amount of gear fished, length of time fished, and any visible information on the nature and amount of catch.

The observer transmitted information via VHF radio to a creel census taker on the beach to assist in identification of individual boats and fishers. The observer was able to recognize completed fishing trips and direct the census taker to intercept fishers either along the shore (for individuals) or at the launch ramp (usually) for boats. Interviews were conducted with such fishers to obtain information on gear type and amount, fishing effort, location, amount of catch and species composition.

Recreational fishing effort appeared to be considerably greater on weekend days and holidays compared to weekdays. To reduce variability associated with estimates of fishing effort, days within a survey period were grouped into sampling strata as (1) weekdays and (2) weekend days and holidays (Malvestuto, 1983). Sampling dates were randomized within each stratum to minimize bias. Weekdays were randomized without replacement in order to obtain better coverage with these strata.

After an initial, intensive frame survey of 14 consecutive days of all-day remote surveillance and creel census, these survey methods were applied on a schedule of either one day from each stratum per week, or two weekday and two weekend/holiday samples per month (depending on the general level of fishing activity). This survey covered the period of July, 1992 through December, 1993 except for September–November, 1992 when the fishery was inactive in the wake of hurricane Iniki.

2.2. Calculation of catch, effort and Catch Per Unit Effort (CPUE)

Values of the major fishery variables, catch, effort, and CPUE, were first estimated individually for each stratum, defined by (1) the quarter of the year (i.e., spring, March–May; summer, June–August; fall, September–November; winter, December–February), (2) whether weekday or weekend/holiday, and (3) the type of gear used. When catch or effort for a number of strata were summed–e.g., across weekdays and weekend/holidays, across gears (normally catch only), across quarters (to obtain estimates for a year or for the full period of the study)–the estimate of variance was the sum of the variances of the strata involved. The following sections describe estimation of variables for the individual stratum (statistics based on Meyer, 1975; Cochran, 1977; Malvestuto et al., 1978; Malvestuto and Knight, 1991). Mathematical notation for these estimates is as follows:

$C_u =$ Total catch derived using CPUE
$c_{ij} =$ Catch of fisher j on day i, where $i = 1 \ldots d$, $j = 1 \ldots n_i$
$d =$ Number of days fishery was observed
$D =$ Total number of days
$E =$ Total effort
$\bar{E} =$ Mean daily effort
$E_{ij} =$ Observed effort of fisher j on day i, where $i = 1 \ldots d$, $j = 1 \ldots N_i$
$f =$ Finite population correction factor for catch and effort $= 1 - (d/D)$
$n_i =$ Number of fishers interviewed on day i
$N_i =$ Number of fishers observed on day i
$U =$ Mean CPUE over all fishers

2.2.1. Effort

An estimate of total effort, E, was obtained by calculating a mean daily effort by all fishers in the stratum combined (using observed effort on each day and the number of observation days) and expanding by the total number of days available for fishing in the stratum, i.e.,

$$E = \bar{E} \times D = \frac{\sum_{i=1}^{d} \sum_{j=1}^{N_i} E_{ij}}{d} \times D. \quad (1)$$

The variance of $\bar{E}$ was estimated as:

$$\operatorname{Var}(\bar{E}) = \frac{\operatorname{Var}(E_{ij})}{d} \times f = \frac{\sum_{i=1}^{d} \left(\sum_{j=1}^{N_i} E_{ij} \right)^2 - d\bar{E}^2}{d(d-1)} \times f, \quad (2)$$

where f was used because (d/D) was frequently > 0.05. The variance of E was estimated as:

$$\operatorname{Var}(E) = \operatorname{Var}(\bar{E} \times D) = D^2 \times \operatorname{Var}(\bar{E}).$$

2.2.2. Catch Per Unit Effort (CPUE)

A mean CPUE, U, over all fishers in a stratum was estimated by obtaining an individual CPUE for each interview, summing over all interviews, and dividing by the number of interviews, i.e.,

$$U = \frac{\sum_{i=1}^{d}\sum_{j=1}^{n_i}\frac{C_{ij}}{E_{ij}}}{\sum_{i=1}^{d} n_i} \tag{3}$$

The variance of U was estimated as

$$\mathrm{Var}(U) = \frac{\mathrm{Var}\left(\frac{C_{ij}}{E_{ij}}\right)}{\sum_{i=1}^{d} n_i} \times f_u$$

$$= \frac{\sum_{i=1}^{d}\sum_{j=1}^{n_i}\left(\frac{C_{ij}}{E_{ij}}\right)^2 - \left(\sum_{i=1}^{d} n_i\right)U^2}{\left(\sum_{i=1}^{d} n_i\right)\left(\sum_{i=1}^{d} n_i - 1\right)} \times f_u, \tag{4}$$

where $f_u = 1 - \frac{d\sum_{i=1}^{d} n_i}{D\sum_{i=1}^{d} N_i}$

is the finite population correction factor, similar to the conventional factor, but adjusted to reflect a ratio of fisher-days with interviews to total fisher-days of the stratum.

2.2.3. Catch

Estimates of total catch (C_u) were calculated as a product of the mean CPUE, mean daily effort, and total number of days in the stratum, i.e.,

$$C_u = U \times \bar{E} \times D$$

from Eqs. (1) and (3) above. The variance of C_u was estimated as Var $(C_u) = D^2\ [\bar{E}^2 \mathrm{Var}\ (U) + U^2 \mathrm{Var}\ (\bar{E}) + \mathrm{Var}\ (\bar{E})\mathrm{Var}\ (U)]$, making use of Eqs. (1)–(4) above.

A separate and direct estimation of catch for each taxon from raw sample data was not feasible because of the relatively small sample size of some identified taxa within a stratum. Therefore, catch estimates for each taxon were derived from the expanded estimates described previously. The raw sample weight of each taxon caught in each stratum was divided by the raw sample weight of the total catch for that stratum to obtain the fractional taxonomic composition. These fractions were then multiplied by the expanded catch for the stratum to obtain an estimated expanded total weight of catch for each taxon.

2.3. Gear, effort, and area fished

Fishing effort for all strata was calculated as hours fished multiplied by the number of units of gear used. The fishery analyzed includes the coastal area within Hanalei Bay and immediately outside the mouth as shown in Fig. 1. A wide variety of types (and units) of gear was employed in the fisheries: hand operated cast (or throw) net; hand lifted crab net; bottom longline; bottom gill net; surround net; portable hand-hauled trap; line or pole-and-line fished from (1) shore or (2) stationary boat; trolling; spear fishing. Surround nets longer than 50 m (typically deployed from boats longer than 6 m) were classified as large surround nets; others were classified as small surround nets. Each gear was examined separately, because fishing power was not comparable among gears.

2.4. Estimations of fish densities

Abundance of fishes on hard substrate was assessed using standard, underwater visual belt-transect survey methods (Brock, 1954; Brock, 1982) over the course of two years that included the period of the fishery survey. Forty-two transects (25 × 5 m) were established in a variety of habitats on hard substrate throughout the bay (Fig. 1). A SCUBA diver swam each transect at a constant speed, identified to the lowest possible taxon all fishes visible within 2.5 m to either side of the center line (125 m^2 transect area), counted them, and recorded the data. Standard length (SL) of fishes was estimated to the nearest centimeter. Extensive training was conducted using PVC pipes of various lengths and spearing and measuring fish to develop skill in estimating lengths. Bell et al. (1985) and DeMartini et al. (1989) found that with practice observers could reliably estimate lengths underwater. Live wet weight, W, of all fishes recorded in all censuses was estimated from the visually estimated SL using the relationship $W = a(SL)^b$. Values of the fitting parameters a and b were derived from previous work of the Hawaii Cooperative Fishery Research Unit or from results of other workers.

3. Results

3.1. Effort

In terms of number of fishers, number of units of gear, and total hours fished, lines fished from shore are the dominant gear type (Fig. 2). They are used for recreational/subsistence fishing by fishers of all ages and economic means. Not surprisingly, weekend/holiday fishing dominates (Fig. 2). Line fishing occurs in the bay almost everywhere the shoreline is accessible and a suitable depth of water can be reached.

Line fishing effort from boats inside the bay (involving greater costs and logistics) was much lower, but important in number of fishers, number of units of gear, and total hours fished. Weekend/holiday activity also dominated the line fishing from boats (Fig. 2), which probably was also largely recreational/subsistence. In contrast to shore fishing, boat fishing tends to be concentrated along the outer edges of reefs and hard bottom and over the sandy bottoms of the central bay. Some of the same reef and shore fishes are available, as well as some sand-bottom species.

The gear with the second highest effort in terms of number of units of gear, total hours fished, and possibly number of fishers, was crab nets (Fig. 2). Most of the effort occurred on weekends/holidays (Fig. 2). Most crab nets were set from boats or (especially) from the Hanalei pier, apparently primarily on sandy bottoms or near reef edges.

Trolling effort was moderate and composed of about equal contributions from weekdays versus weekends/holidays (Fig. 2). Trolling occurred almost entirely in the central bay. Probably almost all trolling was done in the upper portion of the water column for open-water pelagic species.

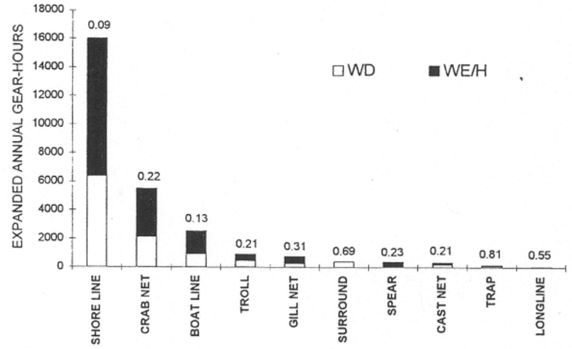

Fig. 2. Expanded annual fishing effort (gear-hours) by gear type (December,1992–November,1993). WD-weekday stratum, WE/H-weekend and holiday stratum. Coefficient of variation (COV) appears on top of each bar.

Gill nets involved relatively few fishers and units of gear, but each net had high fishing power. Effort was considerably greater on weekends (Fig. 2). Nets were set in most areas on both sides of the bay, but effort was concentrated in the estuary and the bay just south of it. Spearing effort was irregular, but much greater on weekends. Relatively few fishers and units of gear were involved. Spear fishing occurred over hard substrate on both sides of the bay. Cast nets were used by relatively few fishers; each fisher operated one net with moderate fishing power. Effort was greater on weekdays. Cast nets were used widely: areas of concentration included the estuary and bay shore south of it and a long stretch of shallow reef flats north of it.

Surround netting was unique in several respects. Long nets with fine mesh were deployed from the surface (often extending the full depth of the water column) to encircle rather large schools of fish, almost always *Selar crumenophthalmus* or *Decapterus* spp. Units of gear were large and had high fishing power, and each typically required several fishers. Size and corresponding fishing power varied greatly among nets. Therefore, the net-hour used in this work is a crude, non-standard unit of effort for surround nets at Hanalei, and aggregated values of effort obtained by summing such dissimilar gear (e.g., Fig. 2, Tables 1 and 2) are difficult to interpret. Timing and frequency of surround net fishing were entirely dependent on discovery of infrequent, large schools of the target species within range of the gear.

Table 1
Characteristics of the total surround net fishery in each quarter of the study, including estimated total surround net catch (C_{TS}) in kg, percentage seasonal distribution of fishing effort (net-hours), and estimates of CPUE and its COV. Hurricane Iniki disrupted data collection in Fall 1992

Quarter	Summer 92	Fall 92	Winter 93	Spring 93	Summer 93	Fall 93	Total
Catch, C_{TS} (kg)	3225	Iniki	0	34807	460	1132	39624
Fishing effort (%)	25	no data	0	65	5	5	
Mean CPUE (kg/net-hr)	39			282	57	168	116
COV	2.82			1.79	1.05		2.59

Relatively few surround net sets occurred in a year. Comparison of weekday versus weekend/holiday effort is probably meaningless. All known surround netting occurred well inside the bay. Some sets were made in the central bay, but most nets (except a few large units set and hauled from boats) were hauled ashore on beaches south and southwest of the estuary.

Effort by all other methods was clearly minor and irregular. Given the low frequency of such fishing and the nature of sampling, no meaningful trends can be inferred for these methods.

3.2. Catch Per Unit Effort (CPUE)

Individual values of CPUE and its coefficient of variation (COV) for each stratum were calculated as described in Section 2. Representative overall values of CPUE (Tables 1 and 2) were estimated for each type of gear within the bay using the same methods on the aggregate of all temporal strata pooled within each gear type. Although COV values at lower levels of aggregation were high, often approaching and sometimes exceeding 1.0, they were generally much lower when pooled by gear type over the entire survey period (Table 2).

Table 2
Mean catch per unit effort (CPUE) and coefficient of variation (COV) for each major type of gear used in the Hanalei fishery, aggregated over annual temporal strata (December, 1992 through November, 1993). N = the number of annual observations per gear type

Gear	Annual CPUE		N	Units of CPUE
	Mean	COV		
Small surround net	45.40	0.33	10	kg/net-hr
Cast net	1.60	0.36	47	kg/net-hr
Gill net	1.25	0.34	26	kg/net-hr
Spear	0.87	0.32	38	kg/spear-hr
Longline	0.64	0.12	2	kg/longline-hr
Troll	0.64	0.59	55	kg/line-hr
Lines from boats	0.26	0.16	151	kg/line-hr
Crab net	0.10	0.35	44	kg/net-hr
Lines from shore	0.07	0.11	686	kg/line-hr

Credible estimates of the general order of overall CPUE were obtained for gears where substantial fishing effort was applied, and some interesting patterns emerged. For lines from shore, the most widely used gear, CPUE (kilograms per line-hr) was low. Considered among gears of generally similar fishing power, or as catch per fisher or fisher-hr, this CPUE was among the lowest in the study. Crab netting showed similarly low CPUE in kilograms per line (net)-hr, but COV was somewhat higher. Since catches in the crab fishery are sporadic, an adequate sampling regime concentrated during peak availability of crabs might produce much larger CPUE. Fishing by lines from boats in the bay was more productive: three or more times the yield per line-hr. As with the other line methods, COV was low. The next most similar method, trolling in the bay, involved a smaller sample, which may have accounted for the higher variability (COV); however, the results clearly suggest an increased CPUE in kilograms per line-hr above the sedentary line methods. This higher CPUE can partially be explained by the larger species targetted by trollers.

For longlines in the bay, the sample size was much smaller, and COV is perhaps surprisingly low. The gear has potentially higher fishing power, and the results may indicate a higher CPUE. For the remaining three inshore gears–spear, gill net, and cast net–COV values are moderate and mostly similar. All these gears appear to have somewhat higher CPUE in terms of kilograms per unit of gear-hr than the previous gears. It is interesting that gill nets, with potentially much greater fishing power per unit of gear, do not produce much larger catches compared to spears and cast nets that are hand operated by one fisher and require active search. The efficiency of spearing in weight collected is probably somewhat increased by selection for larger individual fish.

3.3. Catch

3.3.1. Total surround net fishery

The only major commercial catch from the bay is taken by the surround net fishery. The total catch of this fishery, 'total surround net catch', C_{TS}, is shown for the six quarters of the entire study in Table 1. Fishes caught by this method are almost all small pelagic carangids, *S. crumenophthalmus* and *Decapterus* spp. Effort measured in net-hours was low, but the large nets have great fishing power. Because of the small number of total sets and large range of actual fishing power among nets, the total range of CPUE for the fishing was extreme, and CPUE values should be viewed with caution (Table 1). This large fishery is best considered separately from other fishing within the bay, except for the much smaller catches of these two coastal pelagic species by small surround nets (with a smaller range of fishing power) and a few smaller-scale methods (see below).

3.3.2. Catch by gear type

Catches by small surround nets (C_{SS}) and by all other types of gear are shown in Table 3. It is clear that these catches by small surround net were much greater than all other catches combined. Lines from shore produced the second largest catches inside the bay (Table 3), based on very large effort (Fig. 2) and low individual fishing power. Total catch by lines from boats was somewhat lower, based on much less effort and higher individual fishing power. Cast netting produced the next highest landings, resulting from moderate effort and fairly high fishing power. Trolling provided somewhat lower catches from fairly strong effort and moderate fishing power. Variability (COV) was considerably higher than for other line gears in the bay. Gill nets were next in importance as a result of moderate effort and high fishing power of the gear. Crab netting produced moderate catches from strong effort with relatively modest individual fishing power. The temporal pattern of spearing showed high variability within some quarters and great differences among some quarters. A satisfactory single value representative of the spear fishing annual catch remains obscure; the estimate given ($\sim$ 340 kg/yr, Table 3) may represent a lower bound.

Table 3
Estimates of expanded annual catch (C_u) for December, 1992–November, 1993 derived using expanded effort and CPUE. Catches are in kilograms

Gear	C_u	(COV)
Small surround net, C_{ss}	12150	(0.77)
Lines from shore	1042	(0.51)
Lines from boats	775	(0.74)
Cast net	694	(1.57)
Troll	587	(1.31)
Gill net	485	(1.02)
Crab net	454	(1.18)
Spear	341	(0.94)
Longline	17	(0.00)
Total	16545	

3.3.3. Total catch

The production of fisheries in the bay as a whole can be estimated from these catch estimates. The total annual truly commercial production is not much greater than the 'total surround net catch' (C_{TS}) from Table 1, i.e., about 40,000 kg. This catch consists almost entirely of the two coastal pelagic carangids. The bay does not represent a source or home for these species, but rather a convenient place to catch them. A relatively small amount of this total catch is consumed locally by fishers (and small quantities of a few other species are sold); however, these (and other) species from Hanalei Bay that are consumed locally have significant dietary and cultural value.

The total annual production (commercial and otherwise) might best be estimated by replacing C_{SS} with C_{TS} in the total of Table 3, yielding $\sim$ 44,000 kg. This total is made up of many species, including some that may receive major ecological support from resources of the bay. In view of the unique nature of the small surround net fishery and its target species, another interesting total is the complete annual catch (essentially all recreational/subsistence) of fisheries within the bay other than surround nets, i.e., 3942 kg of finfish plus 454 kg of crabs (from Table 3). The fishes and crabs comprising this catch represent more nearly the resident fauna of the bay.

3.3.4. Annual catch of invertebrates

The fishery took an estimated total of 540 kg of invertebrates annually. These catches included traces of lobsters, octopus, and Samoan crab (*Scylla serrata*), as well as ~ 50 kg of the Kona crab, *Ranina ranina*. The white crab, *Portunus sanguinolentus*, was a major contributor to the annual catch, with 474 kg taken annually. This crab represented over 90% of the total crab net catch, and moderate numbers were also taken by line from shore. Most crabs were caught at the pier by crab net.

3.3.5. Seasonality of catch

The seasonal pattern of the group of more or less resident finfish is shown in Fig. 3 for the five quarters of data for the complete study. The overall catch from the bay does not seem highly variable, although lower in winter. There is a noticeable difference between the two years of the survey in summers; however, if the values for the four contiguous quarters used for annual catch in Table 3 are assumed to be representative, the level of overall catch is perhaps surprisingly stable seasonally. A

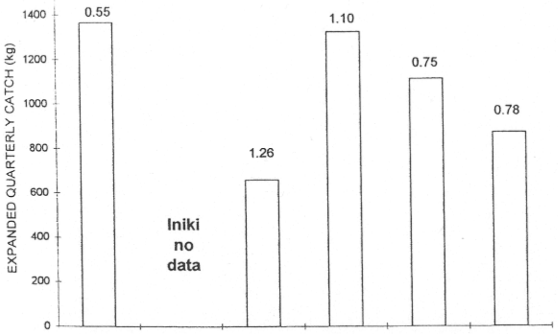

Fig. 3. Expanded quarterly catch (kg) for combined gear types excluding surround nets and crab nets. Gear included cast nets, gill nets, lines from shore and boats, longline, spear, and trolling, and captured the main mix of bay fish species. COV appears on top of each bar. No data during Fall 1992 because of hurricane Iniki.

number of gear types showed pronounced seasonal variation in catches.

Catches by lines from shore and boats were lower in winter. For both gears, the trends followed the general trend of fishing effort. Trolling catches were significant only in the two summers and one spring of the study, consistent with the general pattern of trolling effort. The only prominent seasonal feature in gill netting was the substantially higher catch in the one fall period mentioned. Catches with crab nets (not included in Fig. 3) appeared to be closely associated with Hanalei River discharge. Apparently the turbid water and sediment load discharged during strong freshets provided good conditions for netting crabs in the bay. These relatively brief and sporadic events can cause great variability in catch (and apparently in effort). Freshets tend to be most frequent and strong in winter; a large fraction of all crabs were caught in winter, with moderate-to-minor catches in the other seasons. In the surround net fishery for small pelagic carangids, effort and catch were heavily concentrated in spring, with secondary catches in summer (Table 1).

3.3.6. Catch and standing stock density

Numerical and biomass estimates of fish densitie were calculated for 516 underwater visual censuse on benthic transects over hard substrate. A total o 129 fish species from 28 families was observed. Th overall mean density of individuals was 89.5 per 10 m^2; the absolute number of individuals on a transec census covered a range from five to 981, varyin with bottom relief and habitat complexity. Biomas estimates also were highly variable, with an overal mean density of 7.58 kg per 100 m^2 and a range c 0.13 to 170.5 kg per 100 m^2. The fishery caught 6 fish species from 31 families. Forty species from 1 families were common to the fishery and visua censuses on the hard substrate.

Table 4 shows the composition by family of th annual catch of all finfish except the commercia catches by large surround nets. Small pelagi carangids taken by small surround nets are separate within the table from the other, primarily reside fishes. The latter group is the subject of Figs. 3 and and all subsequent results presented for catch of th fishery. Fig. 4 shows the fractions of the catc provided by the 11 top families in the fishery ar their fractions of the overall mean fish biomass density in visual censuses on the hard substrate of the bay. About 81% of this overall mean biomass density is made up of species that also occur in the catch.

Carangids were clearly the most important family of fishes in the catch, even with the exclusion of the small schooling, coastal pelagic species (Fig. 4, Table 4). They were taken mostly (and about equally) by lines from shore, lines from boat, and trolling, with much smaller catches by gill net and spear. The density of these fishes was low in visual censuses relative to their importance in the fishery. The actual density of these highly transient species is difficult to estimate by visual censuses or other methods. Mullids, acanthurids, and kyphosids were also among the top contributors to the total catch within the bay. Acanthurids were clearly the dominant family by biomass observed in visual censuses. The herbivorous feeding habits of this family exclude them from capture in the line fisheries. Mullids and kyphosids were caught roughly in proportion to their relative abundance observed on transects. Hammerhead sharks (Sphyrnidae) and bonefish (Albulidae) were important in the fishery, but their highly transient behavior over soft-bottom habitats prevented quantitative observations on transects.

Kuhliids provided a significant catch but were poorly represented in censuses. Because of their patchy distribution, cryptic habits, and use of the estuary, the census results may greatly underestimate their density. Lutjanids and scarids were abundant in censuses (lutjanids and mullids essentially equal and ranked 2/3, scarids ranked 4). Both families provided significant catches, but quantities were modest compared to their densities. Most of the remaining families produced rather minor catches, but some species are highly prized (e.g., among the mugilids, priacanthids, and scombrids, and one polynemid species).

Table 4
Composition of finfish catch by family, and visual estimates of densities of those families in hard substrate habitats of the bay

Family	Fishery annual catch (kg)	Visual density estimate (kg/100 m^2)	Visual density rank
Carangidae[a]	13501	0.25	8
Large jacks	1155		
Mullidae	574	0.80	2
Acanthuridae	421	2.88	1
Kyphosidae	304	0.41	7
Sphyrnidae	277		
Albulidae	176		
Kuhliidae	148	0.01	19
Lutjanidae	129	0.79	3
Scaridae	82	0.58	4
Engraulidae	67		
Mugilidae	62		
Muraenidae	56	0.02	16
Labridae	44	0.57	6
Carcharhinidae	33		
Polynemidae	24		
Priacanthidae	24	< 0.01	28
Diodontidae	18		
Scombridae	13		
Sphyraenidae	11		
Cirrhitidae	10	0.09	11
Hemiramphidae	7.3		
Monacanthidae	6.9	0.05	14
Elopidae	4.2		
Fistulariidae	2.3	0.01	21
Dactylopteridae	2.2		
Pomacentridae	2.2	0.57	5
Serranidae	2.1	0.06	12
Aulostomidae	1.6	< 0.01	24
Synodontidae	0.6	< 0.01	26
Tetraodontidae	0.5	0.02	17
Chaetodontidae	0.2	0.15	10

[a]Catch of large surround nets excluded.

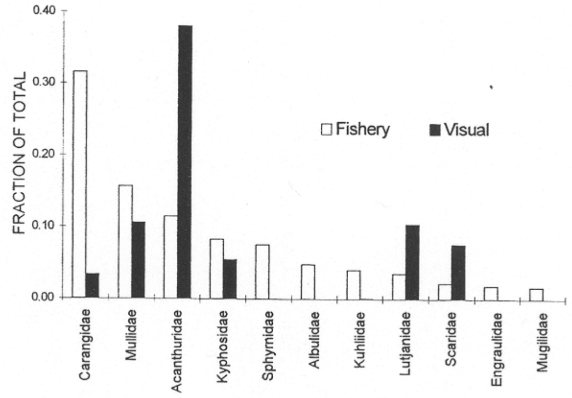

Fig. 4. Fractional composition by family of major components of the finfish catch (kg), and of corresponding components of the visually estimated fish assemblage on hard substrate. Catch of large and small surround nets is excluded.

3.3.7. Trophic composition of catch and fish assemblage

Fishes in the catch and in the visual census were grouped into trophic guilds based on an extensive literature search and unpublished data of the Hawaii Cooperative Fishery Research Unit. Trophic guilds included herbivores, planktivores, piscivores, obligate corallivores, detritivores, feeders on mobile benthic invertebrates (e.g., crustaceans), feeders on sessile invertebrates (e.g., sedentary polychaetes), and feeders on invertebrates of soft sediment (Table 5, Fig. 5).

Considering only the fishes that are more or less resident in the bay (not including small pelagic carangids), on the basis of biomass, piscivores, mobile invertebrate feeders, and herbivores (in descending importance) were the most abundant trophic groups in the catch. Piscivores were caught in large quantity compared to their relatively low visual abundance in the assemblage; mobile invertebrate feeders were caught in much the same high proportion that they occurred; herbivores were fished more lightly relative to their abundance. Trophic guilds observed in visual censuses were significantly different from one another in both number of individuals and biomass (Kruskal–Wallis rank sum test, $\chi^2 = 1868.6$, DF = 5, $P < 0.001$; $\chi^2 = 1547.3$, DF = 5, $P < 0.001$, respectively). Herbivores were most abundant by weight in visual censuses, but not significantly different from mobile invertebrate feeders, which were numerically dominant. The other trophic guilds were much less important in the catch and not prominent in the fish assemblage. Planktivores were moderately abundant in both, and much more important (dominant) in the catch if small pelagic carangids that transit the bay are considered (Table 5, 'Total' catch column).

Table 5
Trophic composition of the finfish catch and of visually estimated density of the fish assemblage on hard substrate. Visual densities that are not significantly different from one another have the same letter designation (Kruskal–Wallis rank sum test: $\chi^2 = 1547.3$, DF = 5, $P < 0.001$, Dunn's multiple comparison procedure, $\alpha = 0.1$)

Trophic guild	Fishery annual catch (kg)		Visual density estimate (kg/100 m^2)	Dunn's grouping
	Total[a]	Bay residents[b]		
Planktivores	12594	248	0.62	B
Piscivores	1280	1280	0.36	C
Mobile invertebrates	1049	1049	2.30	A
Sessile invertebrates	–	–	0.04	D
Herbivores	814	814	4.11	A
Soft sediment	204	204	–	
Detritivores	62	62	–	
Corallivores	< 1	< 1	0.15	C
Total	16003	3657		

[a]Catches of large surround nets excluded.
[b]Small pelagic jacks excluded (large and small surround net catches).

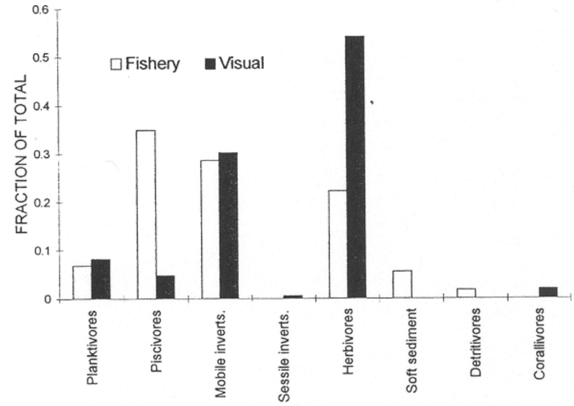

Fig. 5. Fractional trophic composition of the finfish catch (kg), and of the visually estimated fish assemblage on hard substrate. Catch of large and small surround nets is excluded.

Detritivores and soft sediment feeders were identified only among fishes of the soft sediment habitats, whose density was not quantified with the same visual census protocol as fishes of hard substrate. Therefore, no visual density estimate is shown. The 'soft sediment' prey category includes a heterogeneous mixture of epi- and infauna, primarily mobile and sessile invertebrates.

3.3.8. Mobility composition of catch and fish assemblage

Fishes in the catch and in the visual census were grouped into guilds based on degree of mobility (other than regular diel movements away from a home residence) (Table 6, Fig. 6). Residents were defined as those species with limited movement and well defined home ranges. These included species such as squirrelfishes, eels, hawkfishes, and some

Table 6
Mobility composition of the finfish catch and of visually estimated density of the fish assemblages on hard substrate

Mobility guild	Fishery annual catch (kg)		Visual density estimate (kg/100 m^2)
	Total[a]	Bay residents[b]	
Transients	14000	1655	0.28
S2[c]	1098	1098	3.88
S1[d]	679	679	2.85
Residents	228	228	0.57
Total	16005	3660	

[a]Catches of large surround nets excluded.
[b]Small pelagic carangids excluded (large and small surround net catches).
[c]Semi-vagile species that make daily movements on the order of hundreds of meters.
[d]Semi-vagile species that make daily movements on the order of tens of meters.

damselfishes. Transients were capable of rapid travel over relatively large distances and included species such as carangids and some deep-water snappers. Species with intermediate degrees of mobility were classified into semi-vagile groups. Species such as butterflyfishes and small wrasses with daily movement patterns on the order of tens of meters were classified as semi-vagile type I (i.e., S1). Semi-vagile type II species (i.e., S2) made daily movements on the order of hundreds of meters and included groups such as large surgeonfishes and parrotfishes.

Transients (not including small pelagic carangids) were dominant in the biomass of catch, although

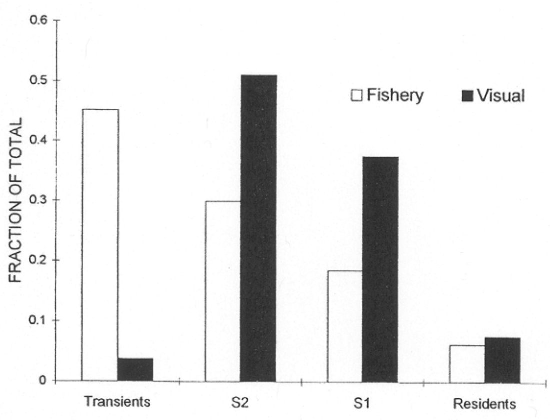

Fig. 6. Fractional composition by mobility guild of the finfish catch (kg), and of the visually estimated fish assemblage on hard substrate. Catch of large and small surround nets is excluded.

they made up a small fraction of the available fish assemblage on hard substrate. (If small pelagic carangids that transit the bay were included, the catch would be even more strongly dominated by transients [Table 6, 'Total' catch column].) The more mobile (S2) and less mobile (S1) groups of semi-vagile fishes were successively less abundant, but important, in the catch; both groups were caught in proportions considerably below their abundance in the habitat. Resident fishes were least important in the catch and were taken in proportion to their abundance. The two semi-vagile guilds (S1 and S2) accounted for a large part (nearly 90%) of the total fish assemblage biomass on hard substrate.

4. Discussion

The stratified random protocol used for monitoring effort and performing creel survey provided a useful sample of almost all types of fishing activity in Hanalei Bay. Within each sampling period, census of almost all fishing effort and more than 70% of all catches was possible because of favorable local geography and the small size of the bay and the fisheries associated with it. These characteristics permitted making a valuable check on the expanded estimate of catch (as described in Section 2. That expanded catch (C_u) based on CPUE and effort was compared to an independent estimate obtained by simply expanding the sums of all catches recorded during sampling periods and correcting for the (known) fraction of all fishing that was creel censused during each sampling period. Agreement between catch estimates by these two methods was reasonably good for most gear types that produced significant catch. The most serious problem with the accuracy and precision of estimates of effort, CPUE, and catch was that relatively low total activity in the small fishery produced infrequent and possibly non-representative records in some strata.

All estimates of fish density were based on underwater visual censuses in daylight over hard substrate. This method is known to produce underestimates of nocturnally active fishes, fishes that reside in crevices, or those that flee approaching divers (Brock, 1954). Although underwater visual census may underestimate nocturnal and cryptic species, compar-

Table 7
Percentages of fish species in a community assigned to different trophic categories. Adapted from Jones et al. (1991)

Source	Hobson (1974)	Hiatt and Strasburg (1960)	This study	Thresher and Colin (1986)	Williams and Hatcher (1983)
Location	Hawaii	Marshall Is.	Kauai	Enewetak	GBR[a]
Trophic guild					
Invertebrate feeders	56	49	43	33	53
Mobile invertebrates	34	35	32	–	45
Sessile invertebrates	13	8	6	–	3
Corallivores	9	6	5	–	5
Herbivores	7	26	30	20	15
Planktivores	18	4	11	38	20
Piscivores	7	10	16	8	8
Omnivores	10	13			4
Others (e.g., cleaners)	2			1	

[a]Great Barrier Reef, Australia.

isons with the results of complete (destructive) sampling of whole fish assemblages indicate that it can give good estimates for most diurnally active fishes (Brock, 1982). No single method exists for accurately censusing a diverse group such as reef fishes, which often have varying degrees of detectability, mobility, and wariness (Thresher and Gunn, 1986). Despite these limitations, underwater visual census is the best single non-destructive method for obtaining estimates of abundance for an entire fish assemblage in such hard-bottom habitats. Comparable visual censuses over open sedimentary substrates were not feasible, so visual density estimates (e.g., Tables 4–6, 8, Figs. 4–6) are only for hard substrates. Limited census work and other extensive visual observations over other substrates (Friedlander et al., 1995) indicated that most demersal fishes that were significant in the fishery were strongly aggregated on or very close to hard substrate (sphyrnids and albulids were exceptions).

Except for the commercial surround net fishery, the fisheries within Hanalei Bay can be characterized as small, multigear, multispecies fisheries with fairly low yield. Almost all fishing effort within the bay is of a recreational/subsistence nature and targets a wide variety of species. These activities are more

Table 8
Estimates of total fish biomass density for various locations in Hawaii. Values are means or mean ranges estimated from visual censuses except when noted

Location	Biomass (kg/100 m^2)	Years	Authors
Various locations, Oahu	0.04–18.60	1950's	Brock (1954)
Waikiki–Diamond Head MLCD[a], Oahu	1.7–3.6	1978–1989	Brock and Kam (1993)
Hulopoe–Manele MLCD[a], Lanai	6.0–34.5	1989–1992	Brock and Kam (1993)
Kaneohe Bay, Oahu	12.46	1966	Brock et al. (1979)[c]
Kaneohe Bay, Oahu	9.20	1977	Brock et al. (1979)[c]
Various locations, Oahu	6.7–12.42	1990–1992	Grigg (1994)
Midway Atoll, NWHI[b]	8.0–18.0	1993	DeMartini et al. (1994)
French Frigate Shoals, NWHI[b]	10.0–17.0	1992	DeMartini et al. (1993)
Hanalei Bay, Kauai	0.37–37.31	1992–1994	This study

[a]Marine Life Conservation District.
[b]Northwestern Hawaiian Islands.
[c]Chemical collections.

frequent during the weekends/holidays and are primarily shore based. Line fishing from shore was the dominant method by fishers of all ages and economic means. Overall effort and catch declined noticeably during the winter periods when poorer weather and rough sea conditions prevented many fishing activities.

With the exclusion of small coastal pelagics, piscivores were the most important trophic guild in the fishery. The catch of this guild consisted mostly of carangids that reach medium-to-large adult size and have considerable association with the bottom. These highly mobile species were not found in high densities on the hard substrate visual transects. Herbivores, principally acanthurids, had the highest densities of any guild on the visual transects. Mobile invertebrate feeders in the catch consisted primarily of mullids, labrids, and lutjanids. Low trophic levels contribute significantly to the fishery (~ 24% herbivorous biomass) - not an unusual feature of small-scale tropical fisheries (Stevenson and Marshall, 1974). However, ~ 54% of the fish community biomass consists of herbivores, and nearly 70% of the fishery is provided by fishes at relatively high trophic levels (piscivores and mobile invertebrate feeders) that make up only ~ 35% of the fish community biomass. Clearly, the average trophic chain is rather long.

Proportions of fish species in different trophic guilds of the community showed similarity across several studies and areas in the Pacific (Table 7). The greatest number of species fed on benthic invertebrates in four of the five studies compared, and the percentages were broadly similar among the studies, both for all benthic invertebrates and for mobile benthic invertebrates. Herbivores were the next most speciose guild in Hanalei Bay and for the Marshall Islands overall. The fraction of all species that were herbivorous at Enewetak was roughly similar. Estimates for the Great Barrier Reef (GBR) and the Kona coast of Hawaii Island were noticeably lower. Planktivores appear to be a somewhat more variable group regionally (Parrish, 1989); the number of species for Hanalei is well within the range reported. Reports of the importance of piscivory in reef communities vary widely; much of this variation may be real, but undoubtedly much is due to differences in sampling methodology (Parrish, 1989). The number of piscivorous species in this study at Hanalei seems fairly representative of results reported in Hawaii.

The transient mobility guild consisted mostly of carangids and was the major mobility guild caught in the fishery. Its dominance in the catch (Fig. 6), even with all small pelagic carangids removed, emphasizes the connection of the bay fisheries with surrounding coastal areas, and suggests the importance of recruitment from outside the bay for some components of the fishery. Clearly the more mobile species support a large portion of the fishery (~ 75% transient plus S2 species), based on an estimated combined density of ~ 55% of censused fishes. This result supports the practical value of focusing on habitat types at a larger scale in efforts to associate fishes with habitat. Kyphosids and acanthurids made up much of the S2 mobility guild in the fishery; small mullids and labrids made up the S1 guild. *Kuhlia sandvicensis* and muraenid eels were the dominant residents in the fishery.

A two-year study of the fisheries of Kaneohe Bay, Oahu was conducted using sample design and data expansion techniques somewhat similar to those of this study (Everson, 1994). Because of the much larger size of Kaneohe Bay and the much greater number of fishers using the resources, direct numerical comparisons of effort and catch with this study are probably not useful; however, consideration of CPUE by gear type provides some interesting comparisons between these two fisheries. The rank order of gear types by CPUE is similar between the two locations. For both fisheries, surround nets provided the highest CPUE, followed by gill nets. Pole and line fishing from shore and boat were combined in the Kaneohe Bay study, with an annual CPUE of 0.31 kg/hr. Whereas line fishing from boats in Hanalei Bay produced a similar CPUE (0.26 kg/line-hr), CPUE for line fishing from shore in Hanalei Bay was substantially lower (0.07 kg/pole-hr), and lower than any other major gear in the Hanalei Bay fishery. It is difficult to compare these results without separation of the line gears from shore and boats in Kaneohe Bay.

Biomass densities observed in this study were within the range of most studies around Hawaii, and slightly greater than biomass from some locations around Oahu, possibly because of lower fishing pressure in the Hanalei area (Table 8). The wide range of biomass estimates in the present study results from reporting means for individual transects and sampling in a very broad range of habitats. Many of the other values listed in Table 8 are means of several locations or are from a limited number of habitats and may not reflect the true variability in each location. Brock (1954) estimated fish biomass using visual censuses on transects, and obtained values ranging from 0.04 kg/100 m^2 on sand flats to 18.60 kg/100 m^2 in areas of high vertical relief. In another study, a rough index of habitat complexity was found to have a strong linear relationship with fish biomass in a number of locations around the island of Oahu (Grigg, 1994). In a companion project to our present study, regression analysis using rigorously quantified measures of habitat complexity showed that such complexity explained much of the variability of the fish assemblages at Hanalei Bay (Friedlander et al., 1995; Friedlander, 1996).

High levels of fishing pressure are expected to affect the abundance of reef fishes. Mean standing stock of biomass of fishes on shallow unfished reefs at two remote uninhabited locations in the Northwestern Hawaiian Islands was about twice as high as means reported from shallow fished reefs in the Main Hawaiian Islands (DeMartini et al., 1996). Several marine life conservation districts (MLCD) around the island of Oahu supported mean standing stocks of fishes 4.5 kg/100 m^2 higher than those of areas open to unrestricted fishing pressure (Grigg, 1994).

The mean density of reef-associated fishes observed during visual censuses on the hard substrate was 7.58 kg/100 m^2 (76 mt/km^2). The overall area of hard substrate (Fig. 1), calculated from detailed digitized maps of the bay, was 3.6 km^2. Using these values, a rough estimate of 274 mt can be obtained for the standing stock of reef-associated finfishes in Hanalei Bay. This is obviously a crude estimate because density estimates varied greatly depending on the habitat type. Estimates of fish standing stock on reefs elsewhere range from 1–20 mt/km^2 using visual observations plus rotenone at Enewetak Atoll (Odum and Odum, 1955) to 43–390 mt/km^2 using blasting on the Great Barrier Reef (Talbot and Goldman, 1972).

The total effective fishing area within Hanalei Bay, including associated soft sediments, is 4.6 km^2. This results in an annual fishery yield for the bay of 3.6 mt/km^2 including small coastal pelagics. The annual fishery excluding these pelagics was substantially lower (0.8 mt/km^2). Yields of fishes from

Table 9
Yields of fishes from small areas of reef fished (adapted from Munro and Williams, 1985; Russ, 1991; Medley et al., 1993)

Location	Area of reef (km^2)	Depth used in area estimate (m)	Groups included in statistics	Yield (mt/ km^2-year)	Reference
American Samoa	3.6	8	fish only	21.2	Wass (1982)
			fish and invertebrates	26.6	
Philippines (Sumilon Island)	0.5	40	demersal fish only	20.2	Alcala (1981)
	0.65	60	demersal and pelagic fish	18.3	
Philippines (Apo Island)	1.56	60	demersal fish and octopus	5.8	Alcala and Luchavez (1981)
			demersal and pelagic fish	11.3	
Papua New Guinea (Tigak Islands)	208.0	30		0.42	Wright and Richards (1985)
Ifaluk Atoll	6		all	5.1	Stevenson and Marshall (1974)
Hanalei Bay, Kauai	4.6[a]	32	all	3.60[a]	This study
			finfish and invertebrates excluding small coastal pelagics	0.91[a]	
			finfish excluding small coastal pelgics	0.80[a]	

[a]Estimate includes associated soft sediment.

small reef areas in other locations in the Pacific cover a wide range (Table 9). These include annual yields of >20 mt/km^2 of demersal fish from a small reef tract (0.5 km^2) in the Philippines (Alcala, 1981) and 0.4 mt/km^2 from a larger area (208 km^2) in Papua New Guinea (Wright and Richards, 1985).

Using the 274 mt value for standing stock at Hanalei, and the annual yield of finfish, excluding coastal pelagics, gives an annual exploitation rate of $\sim 1.33\%$ of the standing stock of the complete assemblage. This low value is still undoubtedly biased high, because a number of the species recorded in the catch were commonly associated with the soft sediments of the bay and therefore were not included in the estimates of standing stock.

The diversity of habitat and environmental resources that Hanalei Bay offers seems to support a relatively large and diverse fish community. Scarids, mullids, and acanthurids were important components of the fisheries and of the censused communities. A small fraction of the overall community standing stock is harvested annually - very low compared to estimates from many other locations in the Pacific. These features suggest that most of the Hanalei Bay fish community is not being severely overfished. However, the small sizes at which some fishes are being caught is a matter of concern for management of the stocks.

The mean standard length (SL) of *Caranx melampygus* examined from the catch was 139.2 mm (SD 56.3 mm), and not more than about 30 of the 1270 individuals measured had reached the size of first reproduction (SFR), i.e., 350 mm SL (Sudekum et al., 1991). This high fishing pressure on very small fish would probably represent recruitment overfishing for the population of this species except that the bay is probably resupplied with recruits and receives adult transients from a wide surrounding area. The mean SL of *K. sandvicensis* was 160 mm (SD 15.4 mm); the strongly dominant modal size was 160 mm, near the upper end of the distribution in the adjacent Hanalei estuary nursery (Harrison et al., 1991). Although fishing pressure on this species may not be especially heavy, the strong concentration of catches at the SFR (150–170 mm SL, Tester and Takata, 1953) suggests the threat of growth overfishing at least. Of the 574 kg annual catch of mullids, about 260 kg were juveniles. This fishery operated on the so-called 'oama run', a phenomenon in which large numbers of a cohort of mullid species at a relatively young juvenile stage move inshore to adult demersal habitat (Harrison et al., 1991). The relatively large catches from heavily concentrated effort at this small size (much below SFR) contribute to growth overfishing and may reduce recruitment of valuable adults.

For all species in the Hanalei fishery, the level of population that is reproductively semi-isolated is probably considerably larger than the bay. Several species in the bay fishery benefit by recruitment from less heavily fished surroundings with more large reproductive adults. However, heavy fishing in the bay reduces the overall pool of developing spawners available from the population. From the perspective of managing complete stocks, the heavy fishing in the bay on very small individuals of a few species such as *C. melampygus* becomes a matter of broader management concern.

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